ELSEVIER

Engineering Geology 56 (2000) 109–123

ENGINEERING GEOLOGY

www.elsevier.nl/locate/enggeo

# Seismic risk assessment of an active fault system: the example of the Tsurugawan–Isewan tectonic line

Y. Kanaori *

*Department of Earth Sciences, Faculty of Science, Yamaguchi University, 1677-1 Yoshida, Yamaguchi City 753-8512, Japan*

**Abstract**

The 185 km long Tsurugawan–Isewan tectonic line (TITL) is one of the major active fault systems in central Japan. The TITL, oriented in a NW–SE-trend, passes through the western part of central Japan, extending from the Sea of Japan to the Pacific ocean. It is composed mainly of five large active faults; from the northwest to southeast, the Kaburagi, Yanagase, Sekigahara, Yoro, and Ise Bay faults. As a case study of seismic risk assessment of an active fault system using the parameter of the average moment-release rate, the seismic risk of the TITL is evaluated in the present paper. The average moment-release rate of an active fault system can be calculated from slip-rates and lengths of constituent active faults. In addition, the latest earthquake of the active fault system if unknown can be inferred from data of historical earthquakes and trench excavations. The total moments, which are accumulated over a duration time from the latest earthquake to the present, are estimated by multiplying the average moment-release rate by the duration time. The total accumulated moments can be used to empirically determine the magnitude of an earthquake which would presently occur. The calculated magnitude for each segment or active fault which constitutes the TITL presently is determined as 7.1 at the maximum. Further, the maximum magnitude of a possible earthquake which would occur after a 100 year durability period of concrete-made structures is estimated as 7.2. This implies that the TITL has the potential of producing earthquakes of *M*7.1 and 7.2 at the present and after 100 years, respectively. The method of seismic risk assessment is important in order to obtain input magnitude data of possible earthquakes for an active fault system, to be used in selecting sites and earthquake-proof designs of large structures in seismically unstable regions. 

*Keywords:* Active fault system; Earthquake-proof design; Inland earthquake; Risk assessment; Seismic moment

## 1. Introduction

An active fault system can be identified as a line linking large active faults. Several active fault systems have been found in central Japan, which is situated at the so-called reflection point of the Japanese Islands (Kanaori et al., 1992a). When an active period begins, a portion or segment of an active fault system starts to rupture, and an earthquake is generated. After seismic ruptures cover all parts of the active fault system, without overlapping, the active period ends. An active fault is regarded as a surface rupture that was created due to the movement of a seismogenic fault (Kanaori et al., 1991).

Kanaori and Kawakami (1996) and Kanaori (1997a) claimed that the 1995 magnitude 7.2 Kobe earthquake was generated by the movement of the 40 km long central segment of the Takatsuki–Rokko–Awaji fault system. It was also pointed out

* Tel./fax: +81-83-933-5753.
*E-mail address:* kanaori@po.cc.yamaguchi-u.ac.jp (Y. Kanaori)


PII: S0013-7952(99)00137-4

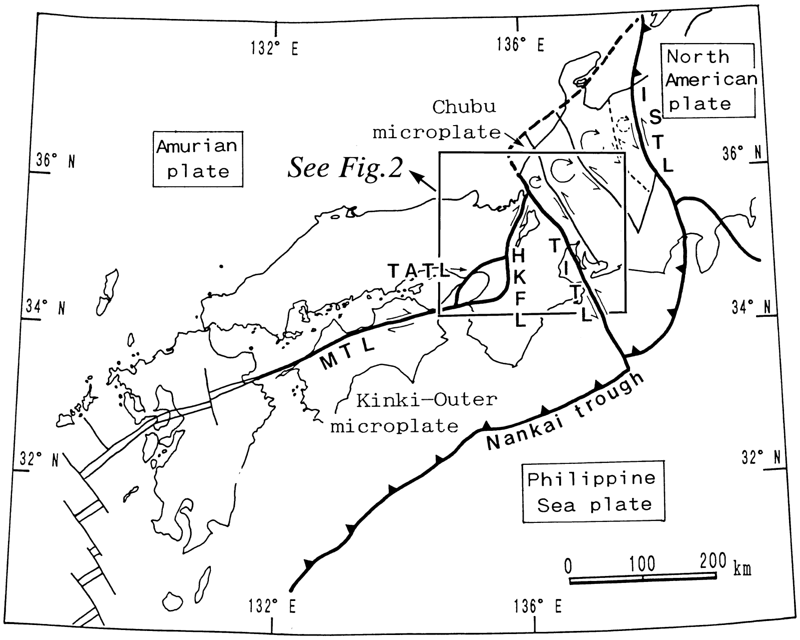


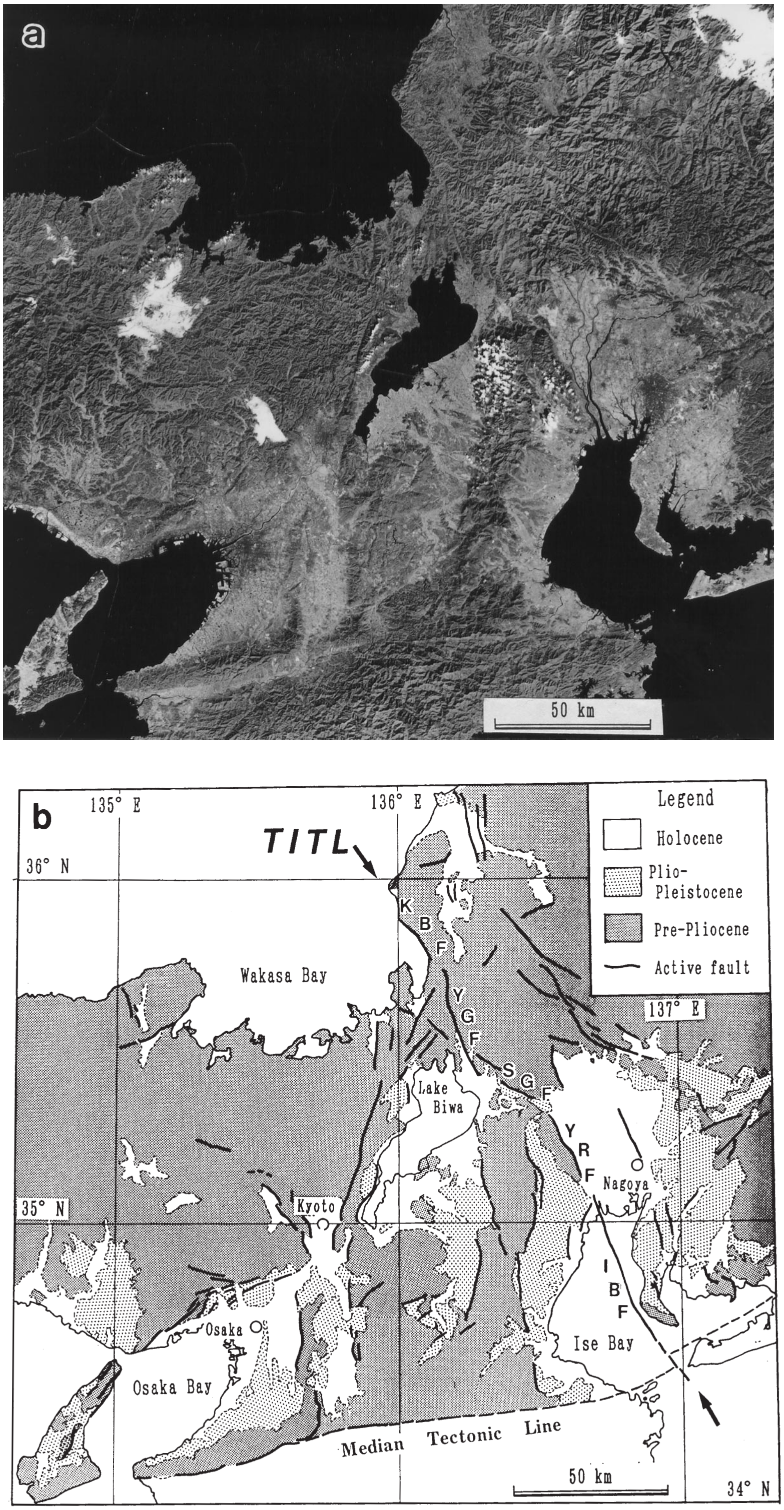

Fig. 1. Tectonic setting of southwest Japan, which is separated into four microplates by active fault systems (Kanaori et al., 1993a). Active fault systems shown are: ISTL, Itoigawa–Shizuoka tectonic line; HKFL, Hanaore–Kongo fault line; MTL, Median Tectonic Line; TATL, Takatsuki–Rokko–Awaji fault system, and TITL, Tsurugawan–Isewan tectonic line. The area enclosed by the rectangle is that shown in Fig. 2.

by Kanaori (1997c) that a central part of the Lake Ohara–W.Yauneyama fault system moved to create the 1997 $M=6.1$ Yamaguchi-ken-hokubu earthquake. Accordingly, it is very important to assess the seismic risk of such active fault systems for natural hazard mitigation of society, and earthquake-proof designs of large structures (Kanaori, 1997b). Kanaori et al. (1992b,c,d) examined the temporal–spatial relationships between destructive earthquakes and active fault systems located in central Japan, and suggested that the average moment-release rate of an active fault system was one of the most important parameters in the seismic risk assessment of the system.

The Tsurugawan–Isewan tectonic line (TITL) is one of the major active fault systems in central Japan. The TITL cuts through the western part of central Japan (Fig. 1). Kanaori et al. (1993a) assumed that the TITL formed a boundary between the Amurian plate and Chubu microplate. The Japanese term 'wan', used in the TITL, is translated into 'bay' in English. Accordingly, Tsurugawan and Isewan mean the Tsuruga and Ise Bays, respectively. Many important structures, such as nuclear power plants, railroads, and highways have been constructed near or crossing the TITL. Furthermore, a new international airport is at planning stage, to be constructed along the TITL in Ise Bay. In order to protect these structures from seismic hazards, the seismic risk of the TITL should be urgently evaluated.

In the present paper, the seismic risk of the TITL is evaluated, using its average moment-release rate, as an example of an active fault

Fig. 2. Landsat-5 image of (a) west-central Japan (reproduced by the permission of the Remote Sensing Technology Center), and (b) a map of the geological (see figure legend) and active fault distribution areas as those of (a) (simplified after Japan Association for Quaternary Research, 1987). Active faults shown in (b) are: KBF, Kaburagi fault; YGF, Yanagase fault; SGF, Sekigahara fault; YRF, Yoro fault, and IBF, Ise Bay fault.


a
50 km
b
135° E
136° E
137° E
36° N
35° N
34° N
TITL
Legend
Holocene
Plio-
Pleistocene
Pre-Pliocene
Active fault
Wakasa Bay
K
B
F
Y
G
F
S
G
F
Y
R
F
I
B
F
Lake
Biwa
Kyoto
Nagoya
Osaka
Osaka Bay
Ise Bay
Median Tectonic Line
50 km

system. First, the average moment-release rate of the TITL is calculated from the average slip-rates of the constituent active faults. Using the average moment-release rate, accumulated moments during the period from the latest earthquake to the present (1998) or after 100 years, are estimated for each segment or active fault which make up the TITL. The accumulated moments can then be used to determine the magnitude of an earthquake which would occur at present, or after 100 years.

## 2. Characteristics of the TITL

### 2.1. Outline

Fig. 2(a) depicts a satellite (Landsat-5) image of west-central Japan. By comparing the satellite image with the geological map shown in Fig. 2(b), the TITL can be easily found on land as a clear NW–SE-oriented lineament. The length of the TITL is estimated to be 185 km.

The TITL is composed of five large active faults. From the northwest to southeast, they are the: Kaburagi, Yanagase, Sekigahara, Yoro and Ise Bay faults (Fig. 3). The length and displacement of each constituent active fault are listed in Table 1. Since the total length of these active faults is

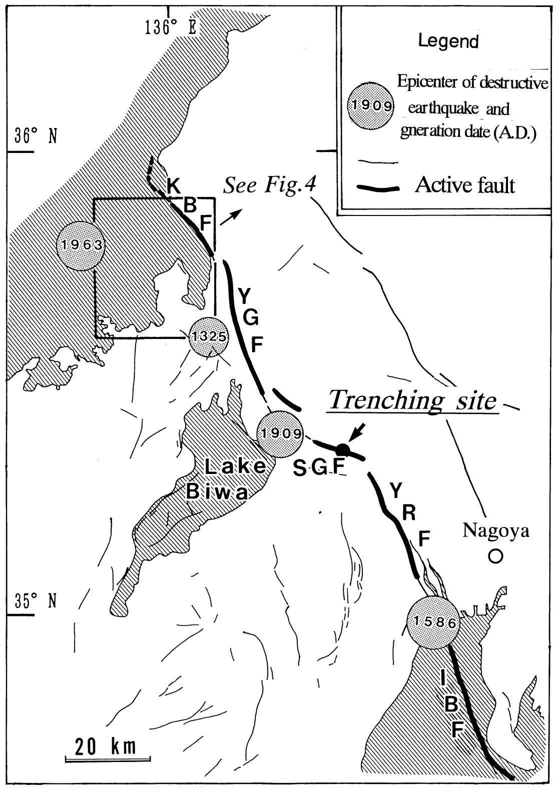



Fig. 3. Locations of active faults (Research Group of Active Faults in Japan, 1991) and epicenters of destructive earthquakes (Iida, 1974; Usami, 1996) along the TITL. The rectangle encloses the area enlarged in Fig. 4.

Table 1
Major active faults which constitute the TITL ($L = 185$ km)

| Fault name | Length $l$ (km) | Displacement $d$ (km) | Displacement Sense | Average slip rate[a] $S$ (mm year$^{-1}$) | Moment-release rate $r$ ($10^{26}$ dyne cm year$^{-1}$) |
|---|---|---|---|---|---|
| Kaburagi | 16 | 0.3–0.5 | Vertical | 0.15–0.25 | 0.0001–0.002 |
| Yanagase | 55 | 1.0[b] | Left-lateral | 0.5 | 0.0014 |
| Sekigahara | 17 | 3.0–4.0[c] | Left-lateral | 1.5–2.0 | 0.0013–0.0017 |
| Yoro | 30 | 0.6–0.8[c] | Reverse | 1.0–1.7[d] | 0.0015–0.0026 |
| | | 5.0[e] | Left-lateral | 2.5 | 0.0038 |
| Ise Bay | 32 | 5.0[e] | Left-lateral | 2.5 | 0.0041 |
| Total fault length, $L$ | 150 | | | Left-lateral total | 0.0106–0.0110 |
| | | | | Vertical total | 0.0016–0.0028 |
| | | | | Total $r$ | 0.0122–0.0138 |

[a] Values with no reference are calculated, using $S = d/t$ ($t = 2$ Ma).
[b] Sugimura (1963).
[c] Research Group for Active Faults in Japan (1991).
[d] Kuwahara (1968).
[e] Kuwahara (1969).

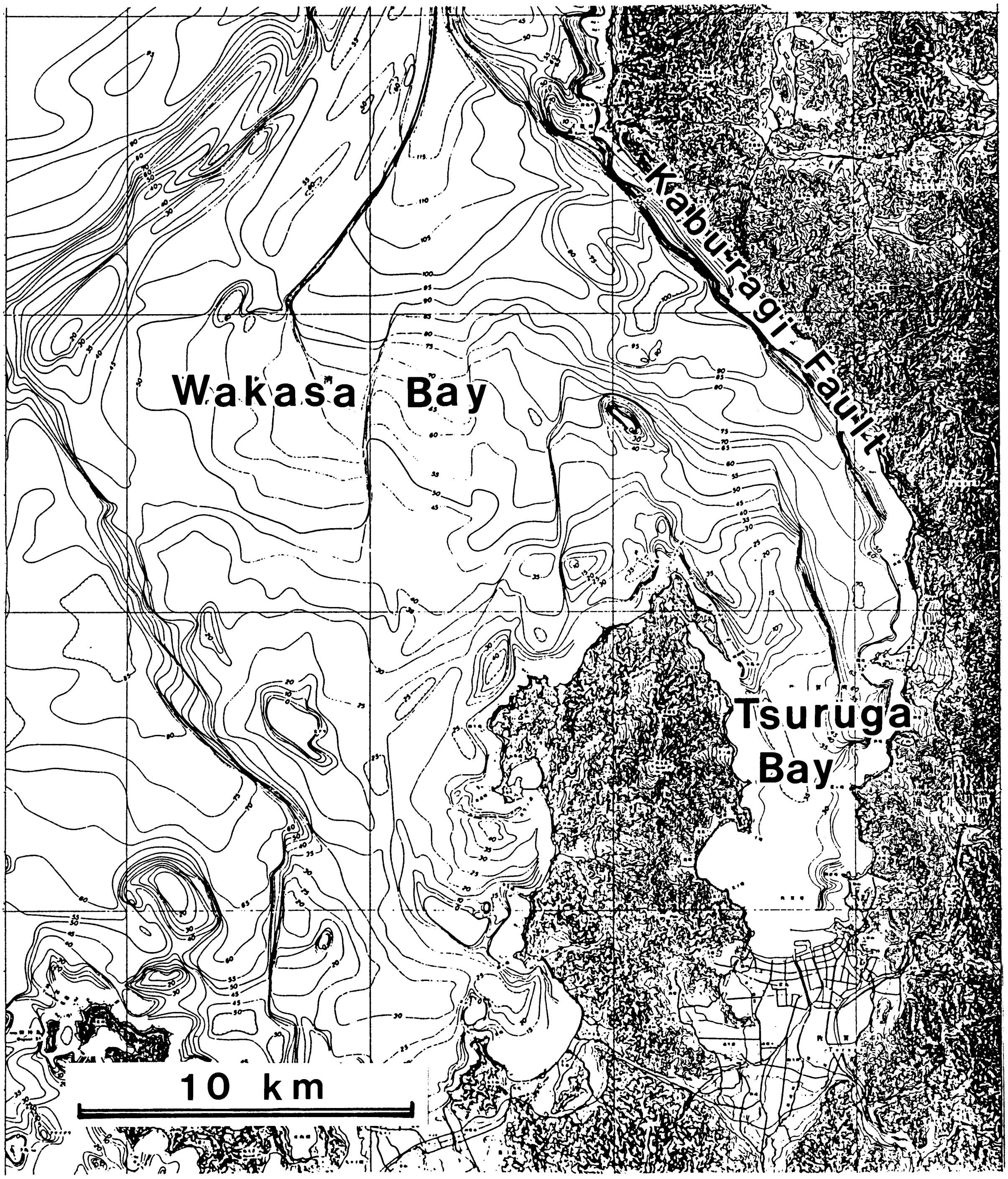



Fig. 4. Topographical map of the sea floor around the Kaburagi fault (Hydrographic Department of Maritime Safety Agency, 1980). The contour interval is 5 m.

150 km, about an 80% (150/185) portion of the TITL appears on the ground surface as active faults.

### 2.2. The constituent active faults

In the northwesternmost part of the region, the TITL is recognized as a NW–SE-trending fault scarp forming a sharp boundary between the mountainous area and Wakasa Bay (Fig. 4). The fault scarp is a manifestation of the Kaburagi fault. The Kaburagi fault extends in a southeasterly direction to the Yanagase fault, which is identified as a clear lineament along a straight deep-eroded valley. The orientation of the TITL veers southeast to east-southeastward along the Sekigahara fault. The Sekigahara fault exists along the northeastern margin of the Sekigahara depression (Fig. 5). Near to the southeast end, the orientation of the TITL turns southeastward. The Yoro fault separates the Yoro mountains to the west and the Nobi alluvial plain to the east, and then submerges under Ise Bay as the Ise Bay fault.

In Ise Bay, multichannel and single channel soundings have been conducted over the past quarter century (Chujo and Takada, 1970; Hydrographic Department of Maritime Safety Agency, 1980, 1995). The results of the soundings are compiled in Fig. 6. This figure clearly illustrates the existence of active faults on the sea floor of


Fig. 5. Aerial photograph of the southern half of the TITL taken from the north (courtesy of Kokusai-Kogyo Co. Ltd.). The Yoro fault exists at the boundary between the Yoro mountains and Nobi Plain. The Sekigahara fault is located along the northern margin of the Sekigahara Depression.

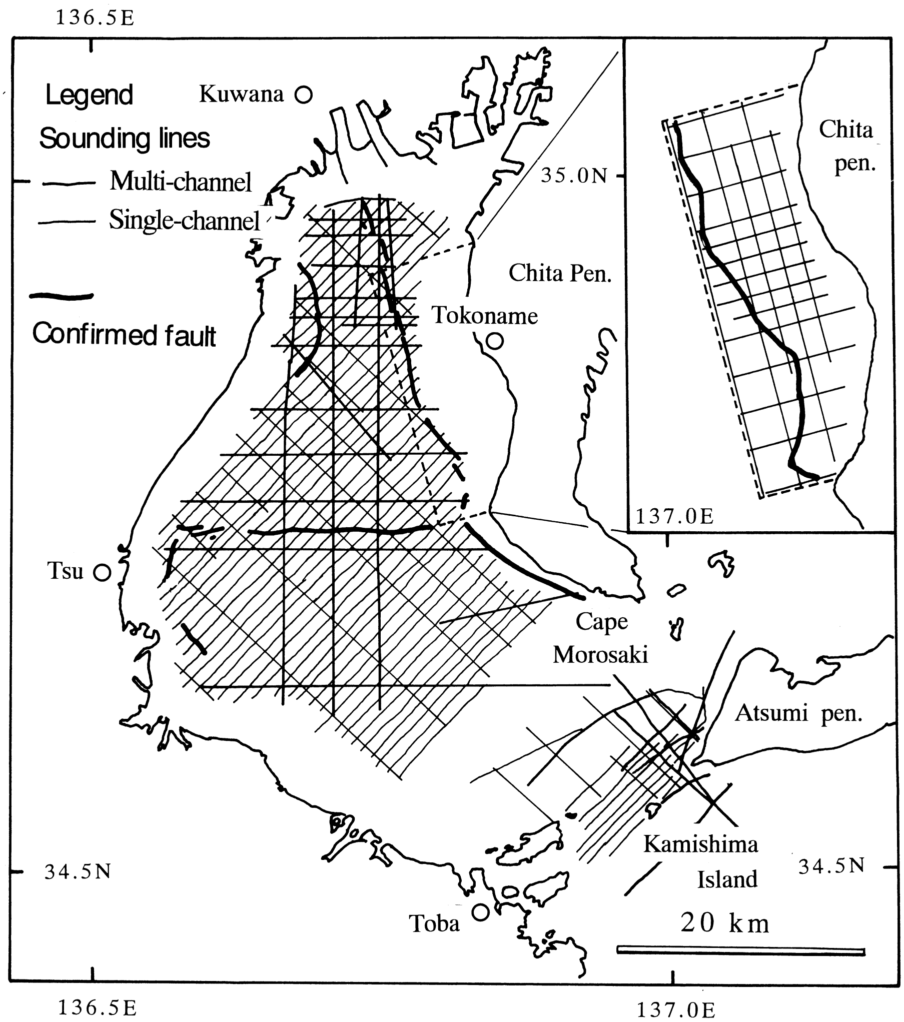



Fig. 6. Map of the active fault distribution in Ise Bay. The data are compiled from Chujo and Suda (1971), Investigation Committee of Chubu Airport (1994), Hydrographic Department of Maritime Safety Agency (1995), Faculty of Science of Kyoto University et al. (1996), and Chubu Regional Construction Bureau (1997). The inset is an enlarged part of the area offshore along the Chita Peninsula.

Ise Bay. The Ise Bay fault extends south-southeastward along the Chita Peninsula, and then curves southeasterly along the top of the peninsula (Fig. 6). The SE-oriented part is named the Utsui fault (Chujo and Suda, 1971). Although extensive geophysical surveys have been performed in and around the mouth of Ise Bay, it is unknown where the Ise Bay fault passes through at mouth of the bay, due to shallow basement rocks and the low resolution of the surveys involved (Inazaki and the Chubu Regional Construction Bureau, 1997).

While the Kaburagi, Sekigahara and Yoro faults are known to have vertical slip components of <0.8 km, the Ise Bay and Yanagase faults have predominant left-lateral slip components (see Table 1). In Ise Bay, it appears that the Ise Bay fault displaces the MTL left-laterally by ca. 5 km (Kuwahara, 1969). The left-lateral offset of the

Yanagase fault is estimated to be 1 km (Sugimura, 1963).

### 2.3. Average moment-release rate

If the length $l_i$ and displacement $d_i$ of an active fault which constitutes a part of the active fault system are given, the moment $mo$ released by the active fault can be expressed as

$$mo = \mu l_i d_i W \tag{1}$$

where $\mu$ is the rigidity of the fault and $W$ the width. The total moments $Mo$ released by all constituent faults can be written as (Kanaori et al., 1992b):

$$Mo = \mu W \Sigma l_i d_i. \tag{2}$$

The average rate $r$ during an arbitrary duration time $t$ can be obtained as

$$r = \frac{Mo}{t} = \mu W \Sigma \frac{l_i d_i}{t_i}. \tag{3}$$

Here, $di/t$ gives the average slip rate $S$ of the constituent fault.

The width $W$ is assumed to equal the thickness of brittle layer in Earth's crust (Scholz, 1990). Microseismicity in this region occurs at depths of $<15$–20 km (Mikumo et al., 1988). In addition, the lower limits of aftershocks of the 1995 Kobe earthquake reached these depths (Hirata, 1995). Accordingly, $W$ is estimated as 15–20 km. In the calculation of the average moment-release rate, $3.4 \times 10^{11}$ dyne cm$^{-2}$ was employed as the value of $\mu$ (Takemura, 1990).

The calculated $r$ values of the faults of the TITL are listed in Table 1. The $Mo$ of the TITL is estimated to range from 0.00122 to $0.00138 \times 10^{26}$ dyne cm year$^{-1}$. The estimated $Mo$ of the TITL is equivalent to those of other active fault systems in central Japan (Kanaori et al., 1992d).

## 3. Destructive inland earthquakes

Since people have lived in the study area since an early historical age, many disasters caused by

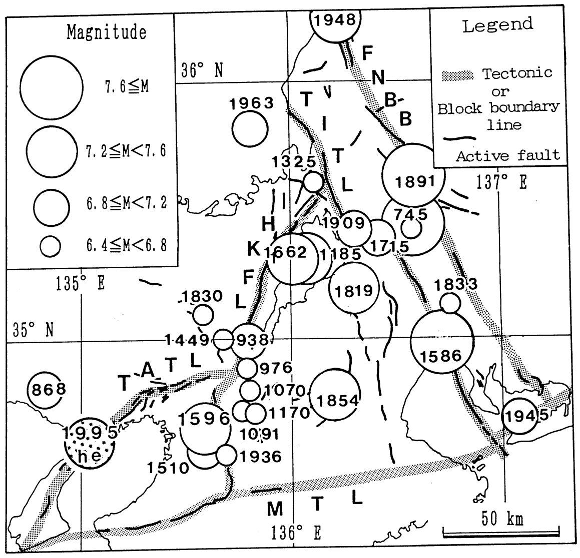



Fig. 7. Epicenters of historical earthquakes which caused damage in west-central Japan. The number shows generation age of the event (A.D.), while the magnitude are presented by the size of the circle (see figure legend). Except for the 1586 event (Iida, 1974), the epicenters are based on Usami (1996).

seismic ground motions have been described in historical documents (Usami, 1996). The estimated epicenters of the destructive earthquakes are shown in Fig. 7. Most epicenters appear to be located along active fault systems.

The occurrence of these historical earthquakes is also supported by a line of evidence of liquefaction and flowage, which have been discovered at a number of historical sites by archaeological excavations (Kanaori et al., 1993b). In addition to this evidence, legends of island submergence in Ise Bay have been passed down from generation to generation. The island submergences are supposed to be caused by movements of active faults (Kanaori, 1998). Based on these historical records and legends, the relationship between earthquake generation and the movement of the TITL can be discussed, as stated below.

### 3.1. Historical earthquakes

Table 2 lists four destructive earthquakes with epicenters found along the TITL. The direct causal relationship between TITL movement and earth-

Table 2
Destructive inland earthquakes which have occurred along the TITL, and their active fault lengths ($l$) and released moments ($mo$)[a]

| Date | Earthquake location (earthquake name) | Magnitude $M$ | Fault length $l$ (km) | Released moment $mo$ ($\times 10^{26}$ dyne cm$^{-1}$) |
|---|---|---|---|---|
| December 12, 1325 | Northern Omi, Wakasa | 6.5 | 10.0 | 0.28 |
| January 18, 1586 | Ise Bay (Tensho) | 7.8 | 60.3 | 13.80 |
| August 14, 1909 | Anegawa (Kono, Anegawa) | 6.8 | 15.1 | 0.69 |
| March 27, 1963 | Off Fukui-ken (Echizen-misaki-oki) | 6.9 | 17.4 | 0.93 |
| Total | | | 102.8 | 15.70 |

[a] Earthquake data are based on Usami (1996).

quake generation is not directly known. However, Kanaori et al. (1992a) claimed that these destructive earthquakes were caused by the movement of segments or active faults which constitute the TITL, since no other major active faults, except for the TITL constituent faults, are found around the epicenters.

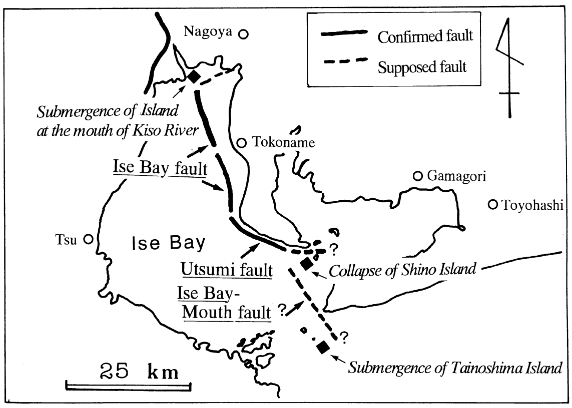



Fig. 8. Possible locations of submerged islands and active faults in Ise Bay and at the mouth of the bay (Kanaori, 1998).

### 3.2. Probable earthquakes inferred from legends

Three legends of submerged islands have been passed down from generation togeneration of the people who lived in areas around Ise Bay. Fig. 8 shows the locations of the submerged islands which are justified from contents of the legends. These island submergences were probably caused by earthquakes accompanying the movement of faults in and at the mouth of Ise Bay (Kanaori, 1998). The possible cause, related faults, and generation year are listed in Table 3. It is likely that these earthquakes were generated by movement of the Ise Bay and Ise Bay Mouth faults, dating back to 862, 1578, and 1586 A.D. (Kanaori,1998).

The earthquake that caused submergence of the islands at the mouth of the Kiso River probably corresponds to the 1586 Tensho earthquake (Iida, 1974). This earthquake has been well documented in historical documents. The other two earthquakes of 862 and 1578, however, have not been correlated with large earthquakes in historical records. Whether or not the two earthquakes occurred should be determined in further studies.

Table 3
Legends of submerged islands in and around Ise Bay, and their probable causal earthquakes and faults (Kanaori, 1998)

| Legend | Cause inferred | Related earthquake | Probable active fault | Remarks |
|---|---|---|---|---|
| Collapse of Shino-jima Island | Fault displacement (vertically 10 m) | The 862 Jokan earthquake | Southeastern extension of the Utsumi fault | The Ise Bay fault moved contemporaneously? |
| Submerged Taino shima Island | Fault displacement (vertically 20 m) | An earthquake in 1578 A.D. | Hypothetical Ise-Bay Mouth fault | The related earthquake was not documented |
| Submerged islands at the mouth of Kiso River | Tsunami and liquefaction | The 1586 Tensho earthquake | Ise Bay fault | The Yoro fault moved contemporaneously? |

## 4. Segmentation of the TITL

The entire length of the TITL does not have to move at one time to create an earthquake, rather a segment or active fault which constitutes the TITL generates an earthquake once during an active period (Kanaori et al., 1991). It is important to divide the TITL into segments or active faults, which have individually caused an earthquake, in order to determine the magnitude of the expected earthquake.

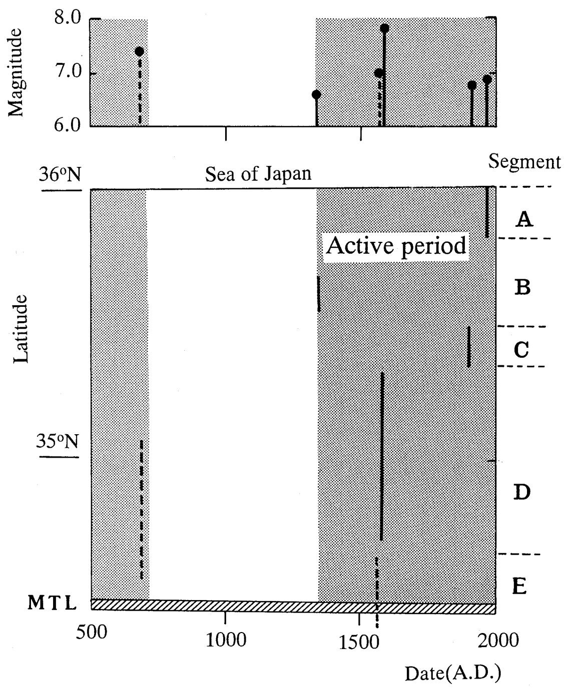



Fig. 9. Temporal–spatial distribution of destructive earthquakes along the TITL. Bold and broken lines denote historically-documented earthquakes and earthquakes inferred from legends of submerged islands, respectively. The length of the line is proportional to the rupture length $l$ which is estimated from the magnitude $M$ using Eq. (3).

### 4.1. Segment or active fault

Fig. 9 shows a temporal–spatial distribution of destructive earthquakes along the TITL. The rupture length $l_i$ of each earthquake is calculated from its magnitude $M$, using the empirical relation (Matsuda, 1975) as:

$$\log l_i \text{ (km)} = 0.6M - 2.9. \tag{4}$$

Kanaori and Kawakami (1997) demonstrated that the magnitude $M$ was overestimated from the fault length $L$, using Eq. (4). The magnitude estimated from the $l_i$ is therefore defined here as the maximum magnitude, $M_{max}$.

It appears from Fig. 9 that an active period began in 1325 A.D. after ca. 500 years of quiescence. During the present active period, the TITL can be divided into five segments, A–E, based on the temporal–spatial distribution of the rupture lengths of historical earthquakes along the TITL. The segments A, B, and C correspond to the Kaburagi, Yanagase, and Sekigahara faults, respectively. Segment D is composed mainly of the Yoro and Ise Bay faults, while segment E is coincident with the Ise Bay Mouth fault.

The segment length $l_i$ and the maximum magnitudes $M_{max}$ of the TITL segments are listed in Table 4.

Table 4
Magnitudes and moments of the maximum earthquakes calculated from the fault length $l$, and elapsed time $t$ since the latest earthquake along segments of the TITL

| Segment name | Fault length $l$ (km) | Maximum earthquake | | Latest earthquake (A.D.) | Elapsed time $t$ (year) (in 1998) |
|---|---|---|---|---|---|
| | | $M$ | $mo$ ($\times 10^{26}$ dyne cm) | | |
| A | 17 | 6.9 | 0.93 | 1963 | 35 |
| B | 30 | 7.3 | 3.06 | 1325 | 673 |
| C | 15 | 6.8 | 0.69 | 1909 | 89 |
| D | 60 | 7.8 | 13.8 | 1586 | 412 |
| E | – | – | – | 1578 | 420 |

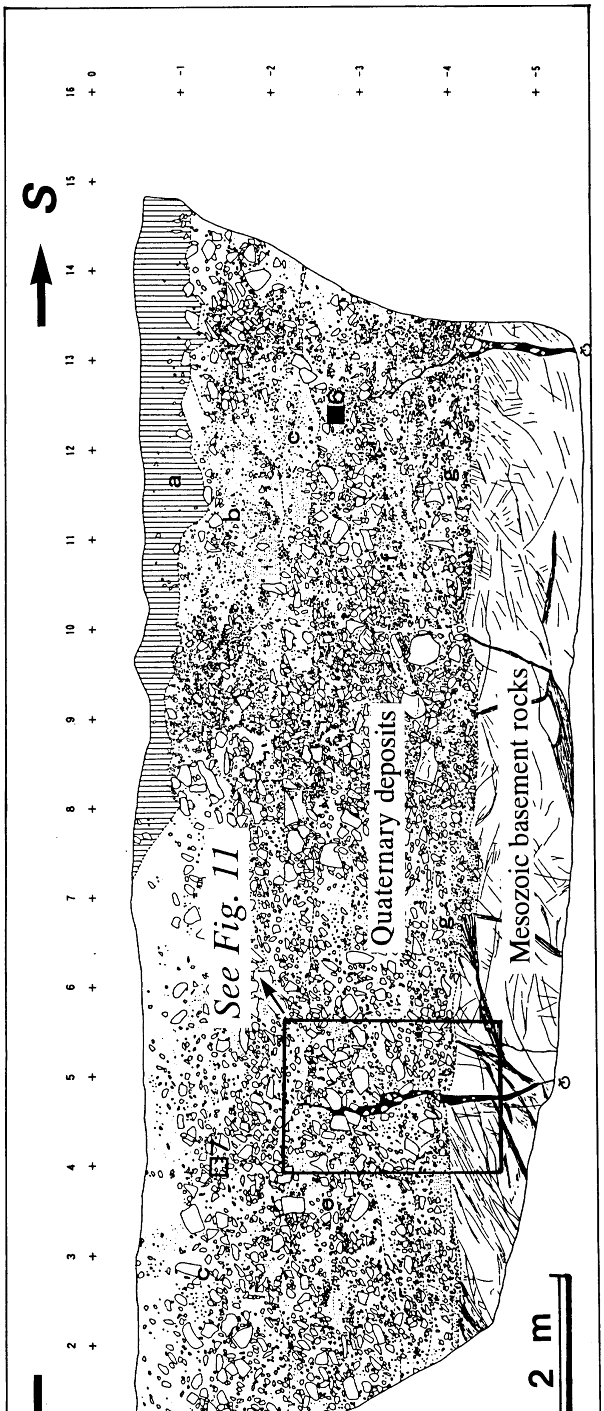



Fig. 10. Geological sketch of a trench wall which excavated on the Sekigahara fault (Gifu Prefecture, 1996). The trenching site is shown in Fig. 3. One continuous open cracks cuts through both Mesozoic basement rocks and Quaternary deposits, shown by the rectangle.

### 4.2. The latest earthquakes along the active faults

The latest activity and elapsed time of each segment are listed in Table 4. Based on trench excavations of active faults, the latest activity along the active faults can be estimated. From trench excavation studies (Geological Survey of Japan, 1994), the latest earthquake on the Yanagase fault is believed to be the 1325 A.D. earthquake.

The 1909 $M=6.8$ Anegawa earthquake occurred close to the northwest end of the Sekigahara fault. Because ruptures accompanying the earthquake were not found on the ground surface (Nakamura, 1910), a seismogenic fault

Fig. 11. Photograph of the open cracks in Fig. 9.

was not clarified. In 1997, a trench was excavated on the central portion of the Sekigahara fault (the trench location is indicated in Fig. 4). Fig. 10 shows a sketch of the trench wall. A few open cracks appear on the trench wall. One open crack seems to originate from Mesozoic sedimentary rocks extending upward to the Quaternary. Fig. 11 is an enlargement of part of the tension crack. The cracks cut through the deposits dated $390 \pm 10$ year B.P. by the $^{14}C$ method (Gifu Prefecture, 1996). Since only the 1909 Anegawa earthquake occurred along the TITL after this date, it is likely that the latest earthquake of the Sekigahara fault corresponds to the 1909 event.

Kanaori et al. (1993a) assumed that the 1963 Off-Echizen earthquake was caused by the movement of parts of the Kaburagi fault. Iida (1974) pointed out, from historical records of Tsunamis, that the epicenter of 1586 Tensho earthquake was located in Ise Bay. Kanaori et al. (1993b) supported Iida's conclusion from the distribution of archaeological sites exhibiting liquefaction and flowage. Therefore, it is presumed that the Tensho earthquake was cased by the movement of both the Yoro and Ise Bay faults.

The Ise Bay Mouth fault likely moved at the time of the 1578 earthquake, which submerged Tainoshima Island, as was shown in Section 4.

## 5. Seismic risk assessment

If the average moment-release rate $r_i$, and the elapsed time $t$ since the latest event along a segment or active fault, are obtained for a segment or an active fault, it becomes possible to calculate the moments which has been stored during a given period. The moments can be changed into the magnitude of an earthquake which would occur at an arbitrary time. The magnitude is significantly important input datum for the earthquake-proof design of large structures.

### 5.1. *Partial moment-release rate $r_i$*

The average moment-release rate $r_i$ of a segment which constitutes an active fault system can be calculated as $r_i = l/L \times r$ (Kanaori and Kawakami, 1997), where $r$ is the average moment-release rate of the active fault system. The $r_i$ value obtained for the TITL segments are listed in Table 5.

### 5.2. *Magnitude potential*

Assuming that the average moment-release rate $r_i$ is constant during an interseismic period, the moments which are accumulated over an elapsed time $t$ from the latest event to the present, are given by $mo = rt$. The accumulated moments $mo$ can be used to determine the magnitude $M$, by an empirical equation as (Wesnousky et al., 1982):

$$\log mo = 17.0 + 1.3M. \tag{5}$$

Because the obtained $M$ denotes that of the earthquake which would presently occur, it is denoted as the magnitude potential $M_p$ (Kanaori and Kawakami, 1997).

In the same manner as the $M_p$, the magnitude potential $M_{p+100}$ of an earthquake that would occur after 100 years can be estimated. The $M_p$

Table 5
Accumulated moments, their filling ratios, and magnitude potential of segments of the TITL

| Segment name | Average moment-release rate $r$ ($\times 10^{26}$ dyne cm year$^{-1}$) | Moments | | Magnitude potential | |
|---|---|---|---|---|---|
| | | Accum. till 1998 ($\times 10^{26}$ dyne cm year$^{-1}$) | Filling ratio (MF ratio) | $M_p$ | $M_{p+100}$ |
| A | 0.00112–0.00127 | 0.04 | 0.04 | 5.1 | 6.3 |
| B | 0.00198–0.00224 | 1.51 | 0.49 | 7.1 | 7.1 |
| C | 0.00099–0.00114 | 0.10 | 0.15 | 6.2 | 6.4 |
| D | 0.00396–0.00448 | 1.86 | 0.14 | 7.1 | 7.2 |
| E | – | – | – | – | – |

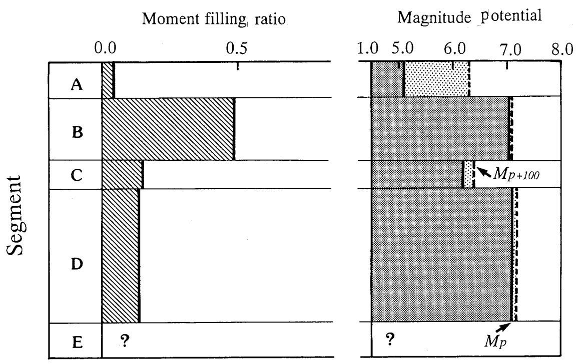



Fig. 12. Diagram showing the moment filling ratio and magnitude potential of segments which constitute the TITL.

and $M_{p+100}$ of the TITL segments are listed in Table 5. The maximum earthquake magnitude which would be created by the rupture of a TITL segment is estimated as up to $M=7.2$ during the next 100 years (Fig. 12). Since the durability period of large concrete-made structures, such as dams and buildings is treated as 100 years, the $M_{p+100}$ are useful input data for earthquake-proof designs.

### 5.3. Moment filling ratio

The magnitude calculated from the fault length $l_i$ using Eq. (3) gives the maximum value of expected earthquakes (Kanaori and Kawakami, 1997). Also, the moments obtained from $M_{max}$ by Eq. (5) give the maximum moments $mo_{max}$.

The ratio of moments stored in a segment or active fault since the latest event to the $mo_{max}$ is defined as the moment filling (MF) ratio. The MF ratio is $<0.5$ for segments of the TITL as found in Table 5. Because the moments are overestimated from the rupture lengths, the true MF ratio is much greater than that obtained above. At any rate, segments or active faults of the TITL have the potential of producing $M=7.1$ and 7.2 earthquakes at the present and after 100 years, respectively (Fig. 12). The magnitudes should be taken into account in earthquake-proof designs of large structures and hazard mitigation in the region along the TITL.

## 6. Concluding remarks

Seismic risk of segments or active faults which constitute the TITL, have been evaluated as a case study of seismic risk assessment of an active fault system using the average moment-release rate. Many active fault systems are found in seismically unstable areas, such as central Japan and western USA. The method of evaluation in the present paper is applicable to other fault systems, in assessing the seismic risk of fault systems that exist in the foundation rock of large structures. Seismic risk assessment is increasingly important for choosing the site and earthquake-proof design of large structures in seismically-unstable areas.

## Acknowledgements

The author wishes to thank Professor S.I. Kawakami of Gifu University for discussions of risk assessment. Thanks are also extended to Drs. H. Iwabuchi of the Maritime Safety Agency and S. Niwa of Geographical Survey Institute for providing geological–structural maps and information concerning faults on the sea floor in Ise Bay. K. Kosaka of Nihon University provided useful critical reviews which improved an early draft of the manuscript. A portion of this research was supported by a Grant-in-Aid from the Ministry of Education, Science, and Culture, and Sports of Japan (No. 08680482).

## References

Chubu Regional Construction Bureau, 1997. Ise Bay Road: Edition of the Bay Mouth Surveys. Chubu Regional Construction Bureau, Japan, (in Japanese).

Chujo, J., Suda, Y., 1971. Gravitational survey of northern Ise Bay. Monthly Rep. Geol. Surv. Japan 22, 15–35.

Chujo, J., Takada, Y., 1970. Geological studies of Chita Bay by the continuous seismic profiling. Monthly Rep. Geol. Surv. Japan 21, 23–54.

Faculty of Science of Kyoto University, Osaka Geo-Research Institute Hanshin Consultants Co. Ltd Chubu Branch Office of JAPEX Geoscience Institute Inc. Water Resources Development Public Corporation Chubu Regional Construction Bureau 1996. Reflection profiles of deep structure across the Kuwana fault and Ise-wan fault. Rep. Coord. Comm. Earthq. Predict. 55, 558–570. (in Japanese).

Geological Survey of Japan, 1994. Strip map of the Yanagase-Yoro fault system 1:100,000. In: Tectonic Map Series 10. Geol. Surv. Japan, Tsukaba, 1 sheet.
Gifu Prefecture, 1996. Gifu Prefecture Report of Investigation Results of the Sekigahara Fault. Gifu Prefectural Government, Gifu. (in Japanese).
Hirata, S., 1995. In: Aftershock Activity Accompanying the Kobe Earthquake vol. 65. Iwanami, Tokyo, p. 199, (in Japanese).
Hydrographic Department of the Maritime Safety Agency, 1980. 1:50,000 Marine Base Map along the coast of "Eastern Wakasa Bay". Report of Topography and Geology on Sea Floors. Hydrographic Department of the Maritime Safety Agency. 1 sheet.
Hydrographic Department of the Maritime Safety Agency, 1995. Geological Structural Map of Sea Floors 1:000,000 "Ise Bay". Hydrographic Department of the Maritime Safety Agency. 1 sheet.
Iida, K., 1974. Historic Earthquakes and Hazards in Nagoya City. Earthquake Subgroup of Aichi Prefecture Earthquake Preventing Committee, Public Office of Nagoya, p. 88 (in Japanese with English abstract).
Inazaki, F., The Chubu Regional Construction Bureau 1997. Seismic reflection survey at the entrance of Ise Bay. Abstract Earth & Planetary Science Joint Meeting. Abstract Earth & Planetary Science, Japan.
Investigation Committee of Chubu Airport, 1994. Results of Geological Investigation of the Candidate Site of the New Chubu International Airport. Investigation Committee of Chubu Airport, Japan, p. 88 (in Japanese).
Japan Association for Quaternary Research, 1987. 1:1,000,000 Quaternary Maps of Japan. Tokyo University Press, Tokyo.
Kanaori, Y., 1997a. Causal relationship between generation of the 1995 *M*7.2 Hyogo-ken-nanbu earthquake and movement of the Takatsuki-Rokko-Awaji tectonic line. J. Geotech. Eng. 568, 1–12, (in Japanese).
Kanaori, Y., 1997b. Earthquake proof design and active faults. In: Dev. Geotech. Eng. vol. 81. Elsevier, Amsterdam.
Kanaori, Y., 1997c. Seismic risk assessment of active fault systems in the western Chugoku district of southwest Japan. J. Nat. Disas. Sci. 9, 9–29.
Kanaori, Y., 1998. Three legends of submerged islands and activity of the Ise-Bay fault. J. Japan Soc. Nat. Disas. Sci. 17, 327–388. (in Japanese with English abstract).
Kanaori, Y., Kawakami, S.-i., 1996. The 1995 7.2 magnitude Kobe earthquake and the Arima-Takatsuki tectonic line: implications of the seismic risk for central Japan. Eng. Geol. 43, 135–150.
Kanaori, Y., Kawakami, S.-i., 1997. Risk assessment for destructive inland earthquakes: application to fault systems in central Japan. In: Kanaori, Y. (Ed.), Earthquake Proof Design and Active Fault. Elsevier, Amsterdam, pp. 217–246.
Kanaori, Y., Kawakami, S.-i., Yairi, K., 1991. Space–time distribution patterns of destructive earthquakes in the inner belt of central Japan: activity intervals and locations of earthquakes. Eng. Geol. 31, 209–230.
Kanaori, Y., Kawakami, S.-i., Yairi, K., 1992a. The block structure and Quaternary strike-slip block rotation of central Japan. Tectonics 11, 47–56.
Kanaori, Y., Kawakami, S.-i., Yairi, K., 1992b. Space–time distribution patterns of destructive earthquakes in the Kinki district of central Japan: implications of the Hanaore-Kongo fault and Tsurugawan-Isewan tectonic lines. J. Jpn. Soc. Eng. Geol. 33, 187–201, (in Japanese with English abstract).
Kanaori, Y., Kawakami, S.-i., Yairi, K., 1992c. Space–time distribution patterns of destructive earthquakes in the inner belt of central Japan (part 2): moment-release rates and earthquake prediction. Eng. Geol. 32, 113–122.
Kanaori, Y., Kawakami, S.-i., Yairi, K., 1992d. Space–time distribution patterns of destructive earthquakes in the inner belt of central Japan (part 3): seismic hazard assessment. Eng. Geol. 33, 99–110.
Kanaori, Y., Kawakami, S.-i., Yairi, K., 1993a. Space–time correlation between inland earthquakes in central Japan and great offshore earthquakes along the Nankai trough: implication for destructive earthquake prediction. Eng. Geol. 33, 289–303.
Kanaori, Y., Kawakami, S.-i., Yairi, K., Hattori, T., 1993b. Liquefaction and flowage at archaeological sites in the inner belt of central Japan: tectonic and hazard implication. Eng. Geol. 35, 65–80.
Kuwahara, T., 1968. The Nobi basin and its fault block movements. Quat. Res. 7, 235–247, (in Japanese with English abstract).
Kuwahara, T., 1969. Ise Bay: subsidence basins centering Ise Bay and neotectonics of southwest Japan. In: Abstr. Symp. Coastal Plain by Geol. Soc. Japan. Geol. Soc. Japan, Japan, pp. 21–30, (in Japanese).
Matsuda, T., 1975. Magnitude and recurrence interval of earthquakes from a fault. Zisin 28, 169–283. (in Japanese with English abstract).
Mikumo, T., Wada, H., Koizumi, M., 1988. Seismotectonics of the Hida region, central Japan. Tectonophysics 147, 95–119.
Nakamura, S., 1910. Overview of research on the Kono (Anegawa) earthquake of 1909. J. Geogr. Geol. 22, 18–27, (in Japanese).
Research Group for Active Faults in Japan, 1991. Active Faults in Japan, Sheet Maps and Inventories. Tokyo University Press, Tokyo, (in Japanese with English abstract).
Scholz, C.H., 1990. The Mechanics of Earthquakes and Faulting. Cambridge University Press, Cambridge.
Sugimura, A., 1963. Yanagase fault. Quat. Res. 2, 220–231, (in Japanese with English abstract).
Takemura, M., 1990. Magnitude-seismic moment relations for the shallower earthquakes in and around Japan. Zishin 2 (43), 257–265, (in Japanese with English abstract).
Usami, T., 1996. Descriptive Catalogue of Disastrous Earthquakes in Japan. new edition. Tokyo University Press, Tokyo, (in Japanese).
Wesnousky, G.S., Scholz, C.H., Shimazaki, K., 1982. Deformation of an island arc: rates of moment release and crustal shortening in intraplate Japan determined from seismicity and Quaternary fault data. J. Geophys. Res. 87, 6829–6852.